Lambert SM, Pickert V, Atkinson DJ, Zhan H. **Transformer based equalisation circuit applied to n-number of high capacitance cells.** *IEEE Transactions on Power Electronics* 2015, (99), 1-10.

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**DOI link to article:**

http://dx.doi.org/10.1109/TPEL.2015.2424075

**Date deposited:**

13/07/2015
Transformer based equalisation circuit applied to n-number of high capacitance cells

Simon M. Lambert, Volker Pickert, David J. Atkinson, Huaxia Zhan
School of Electrical and Electronic Engineering, Newcastle University
Merz Court, Newcastle upon Tyne, NE17RU, UK, England

Abstract -- Over the last decade various high capacitance devices have become available on the market such as supercapacitors, ultracapacitors and recently, Li-ion capacitors. The cell voltage limit of each of these technologies is a small percentage of the system level voltage so they must therefore be connected in series to attain a high voltage. During charging and discharging, manufacturing tolerances between the cells result in voltage mismatch across the stack. Mismatched voltages are an inefficient use of the energy storage medium and can lead to dangerous failures in the cells if voltages exceed safety limits. Transformer based voltage equalisation techniques are the preferred circuit topologies in applications with low system voltage due to simplicity of control and low number of switches. The drawback of these circuits is the number of isolated windings which are required on a single core. This paper describes for the first time a solution to that problem by using a classical two windings transformer that in principal can be applied to any number of capacitors. The paper describes the operation of the circuit, shows simulation results and practical results based on a prototype with 5 cells.

Keywords: Li-ion capacitor; Voltage Equalisation;

I. INTRODUCTION

High capacitance devices such as supercapacitors or hybrid capacitors have a high power density and cycle-life compared to battery technology. Supercapacitor technology is an excellent candidate for hybrid drivetrains (either using internal combustion engine or fuel cell power plants) in electric vehicles as they can provide the high dynamic response required for good acceleration and regenerative braking [1-3]. Besides electric vehicles supercapacitors have also been suggested in general electric drives applications [4, 5] as well as earth moving equipment [6], renewable generation [7], subways [8] and smart-grid/micro-grid applications [9-11].

In 2008 Li-Ion capacitors (made by JM Energy) became available onto the open market. Since 2009 the family of cells has grown and at the time of writing includes 1100F and 2200F pouch cells and 2300F and 3300F prismatic cells [12]. These hybrid cells have higher cell voltage and increased power and energy density compared to more traditional supercapacitor technology whilst maintaining the power density and cycle-life performance. With higher cell voltage, fewer series-connected cells are required to reach a given voltage. The Li-ion capacitor is therefore suitable (if not more so) for applications where traditional supercapacitors have been proposed as the energy storage system.

As with supercapacitor technology, manufacturing tolerances result in variation of the parameters of these cells such as capacitance and series resistance from cell to cell. For a series connection of cells (required to attain system level voltages) these mismatched parameters will lead to unequal voltages across the stack of cells. Operating the cells outside of their voltage range can lead to failure of cells whilst limiting charging when one cell reaches maximum voltage does not utilise the energy storage potential of the stack efficiently [13].

Whilst some simple systems exist for resistive cell discharging to attain equalisation these techniques are too inefficient for many applications and are not considered here. A number of equalisation scheme converters have been proposed in literature (inductor-less, bi-directional buck-boost, transformer based) which are, in theory, much more efficient than the resistive discharging methods. Detailed examination of these converters is beyond the scope of this paper, however, analysis of a representative sample of existing equalisation schemes can be found in another publication by the authors [14].

Two of the most common transformer based voltage balancing circuits are shown in Figure 1. Figure 1a shows the Flyback converter with distributed secondary windings and Figure 1b shows the Forward converter with distributed primary windings. Both converters were originally presented for the purposes of voltage equalisation in [13] and show significant performance advantages compared to the performance of inductor-less schemes and bi-directional buck-boost balancing circuits. In transformer based voltage balancing circuits the transformer provides galvanic isolation which is required for energy transfer between non-adjacent cells.
The four distinct periods are the magnetising period (Figures 3a & 4a) and the demagnetising period (Figures 3c & 4c), which are separated by the dead time. The equalisation scheme operates in four distinct periods. For simplicity the operation is explained on the five capacitor cells converter (Figure 2b) charging capacitor C1 has a higher voltage than C3. The four distinct periods are the magnetising period (Figures 3a & 4a) and the demagnetising period (Figures 3c & 4c), which are separated by the dead time period (Figures 3b & 4b). After the demagnetising period a non-conduction period applies (Figures 3d & 4d). The operation within each of the four periods is described below in more detail. The description assumes ideal components and a transformer ratio of 1:1. However, the internal resistances of the MOSFETs and diodes are included in the following discussion as they determine the rate of cell voltage change as shown later.

II. PROPOSED CONVERTER TOPOLOGY AND OPERATION

Figure 2(a) shows the proposed equalisation converter for n-number of capacitors and Figure 2(b) shows the circuit for 5 capacitors. The converter consists of three parts: a solid-state power MOSFET multiplexer, a standard two windings transformer and a selector circuit. The solid-state MOSFET multiplexer comprises n+1 MOSFET pairs (S₁ to Sₙ₊₁), where n is the number of capacitor cells. MOSFETs in each pair are connected in a totem-pole arrangement and controlled by one control signal; thus both MOSFETs are either ON or OFF at the same time. The role of the MOSFET power multiplexer is to connect the cells that need to be discharged and charged to the rest of the equalisation circuit. The second part of the circuit is the transformer itself. A classical two windings transformer is used with coils wired in opposing polarity. The third part is the selector circuit that consists of four MOSFET switches; ST₁a, ST₂a, ST₁b, ST₂b. ST₁a and ST₁b are connected in a totem-pole arrangement (“1” indicates that both MOSFETs are connected to coil 1) and so are ST₂a and ST₂b (“2” indicates that both MOSFETs are connected to coil 2). Each selector MOSFET is controlled independently. The selector switches are required to apply the correct winding (coil 1 or coil 2) to the capacitor cell for the energising and de-energising process. Figure 2 shows that each selector MOSFET has also anti-parallel diodes added. These diodes are added because they have lower on-state voltage than the body diodes of the MOSFETs.

It would be possible to replace the transformer and selector with an H-bridge arrangement – removing the second winding. However, the structure of the multiplexer would mean that each switch of the H-bridge would have to be bidirectional and losses would be higher thus this concept is not considered in this paper.

The equalisation scheme operates in four distinct periods. For simplicity the operation is explained on the five capacitor cells converter (Figure 2b) charging capacitor C3 from capacitor C1 (assuming that C1 has a higher voltage than C3). The four distinct periods are the magnetising period (Figures 3a & 4a) and the demagnetising period (Figures 3c & 4c), which are separated by the dead time period (Figures 3b & 4b). After the demagnetising period a non-conduction period applies (Figures 3d & 4d). The operation within each of the four periods is described below in more detail. The description assumes ideal components and a transformer ratio of 1:1. However, the internal resistances of the MOSFETs and diodes are included in the following discussion as they determine the rate of cell voltage change as shown later.
**Figure 2** – Proposed equalisation circuit for (a) n-number of capacitors (b) 5 capacitors

**Figure 3** – Operational periods of the proposed converter based on a five cell converter and energy transfer from C1 to C3 showing (a) demagnetising period, (b) dead-time period, (c) demagnetisation period and (d) the non-conduction period
Figure 4 – Idealised transformer waveforms for energy transfer from capacitor cell C1 to capacitor cell C3 during (a) demagnetising period, (b) dead-time period, (c) demagnetisation period and (d) the non-conduction period

Period 1 – t₀ to t₁ – Magnetisation period

The source capacitor C₁ is connected across coil 1 of the transformer via the two multiplexer switches S₁ and S₂, the selector switch ST1a and diode D1b. All devices are on for the entire magnetisation period.

In this arrangement the capacitor cell voltage \( V_{C1} \) of capacitor C₁ is applied across the winding of coil 1 via the switches and current in the circuit in coil 1 begins to rise. The transformer voltages and currents can be derived and the equations are shown in (1) – (4), where \( v_{L1}(t) \) and \( v_{L2}(t) \) are the actual voltages across coil 1 and coil 2 respectively, \( i_{L1}(t) \) is the positive current in coil 1 which is defined as per coil dot convention and \( i_{L2}(t) \) is the current in coil 2, \( R_{ch} \) is the channel resistance of the individual multiplexer MOSFETs S₁ and S₂ and the selector MOSFET ST1a (for simplicity it is assumed that the channel resistance of all MOSFETs are the same), \( R_D \) is the resistance of the anti-parallel diodes in the Selector and \( L_1 \) is the inductance of coil 1.

\[
\begin{align*}
v_{L1}(t) &= L_1 \frac{di_{L1}(t)}{dt} \\
v_{L2}(t) &= -L_1 \frac{di_{L1}(t)}{dt} \\
i_{L1}(t) &= \frac{V_{C1}}{5R_{ch} + R_D} \left( 1 - e^{-\frac{5R_{ch} + R_D}{L_1}(t-t_0)} \right) \\
i_{L2}(t) &= 0
\end{align*}
\]

The amount of energy that has been transferred into the transformer can be calculated with (5):

\[
E = \int_{t_0}^{t_1} V_{C1}i_{L1}(t)\,dt
\]

Period 2 – t₁ to t₂ – Dead time period

In order to transfer the stored energy from coil 1 to capacitor C₃ the multiplexer switches S₃ and S₄ must turn on. However, before S₃ and S₄ can be turned on, S₁ and S₂ must be switched off otherwise a short circuit is produced between capacitor C₁ and C₂ as well as C₂ and C₃. Thus, in Period 2 switches S₁-S₄ are all off. The length of the dead time is determined by the turn-off time of the MOSFETs at maximum current level. For simulation and practical work a fixed time of 500ns has been identified as sufficient. In the dead time period voltage and current levels are assumed to remain constant.

During the dead time period both coils of the transformer become open-circuit generating an elevated voltage across coil 1 and also hence coil 2. In order to reduce the voltage peak a pair of Zener diodes has been added to each coil (Figure 2). Each pair is connected in an anti-parallel arrangement thus one Zener diode is forward-biased and the other Zener diode is reversed-biased for a coil voltage spike of either polarity. This arrangement clamps the voltages across the coils to a maximum value, \( V_{clamp} \), in order to protect the switching devices.

The value of the clamp voltage \( V_{clamp} \) should be at least equal to the initial coil voltage level at the beginning of the demagnetisation process. In practice the initial coil voltages vary with the sink capacitor voltages. Therefore a clamp voltage value of twice the maximum rated capacitor voltage is sufficient. The Li-ion capacitors used in this project had a maximum voltage of 3.8V resulting in a clamp voltage of 7.6V. Since Zener diodes are available in discrete Zener voltages the diode used has next Zener voltage up; 8.2V.

With a clamp voltage of 8.2V and assuming that each Zener diode has the same internal resistance when conducting in both forward and reverse the winding currents and the coil voltages during the dead-time period can be written as:

\[
\begin{align*}
v_{L1}(t) &= V_{clamp} \\
v_{L2}(t) &= -V_{clamp} \\
i_{L1}(t) &= \frac{V_{clamp}}{2R_{Zener}} \\
i_{L2}(t) &= \frac{V_{clamp}}{2R_{Zener}}
\end{align*}
\]

Although in this period there is conduction in the Zener diodes and hence the dead time period produces losses, the duration of this period is much smaller compared to the other periods and hence losses in this period are neglected. Therefore the stored energy in the transformer at the end of the dead time period \( (t = t_2) \) is considered equal the energy at the end of the magnetisation period \( (t = t_1) \), hence (10):

\[
E(t_2) = E(t_1)
\]

Period 3 – t₂ to t₃ – Demagnetisation period

With S₁ and S₂ OFF and S₃ and S₄ ON the sink capacitor C₃ is connected across coil 2 of the transformer. The stored transformer energy can now be released via coil 2. Current is flowing through the multiplexer MOSFETs S₃ and S₄, the selector MOSFET ST2b and the anti-parallel diode D2a.
which are all conducting current during the demagnetisation period. The selector switch ST2a is not turned-on and its anti-parallel connected diode D2a is used to stop reverse current once the coil MMF has collapsed.

Equations (11) to (14) describe the voltage and current waveforms for the demagnetisation period.

\[ v_{L1}(t) = L_1 \frac{di_{L1}(t)}{dt} \]  
(11)

\[ v_{L2}(t) = -L_1 \frac{di_{L1}(t)}{dt} \]  
(12)

\[ i_{L1}(t) = 0 \]  
(13)

\[ i_{L2}(t) = I_{L2}(t_4) - \frac{V_{C3}}{5R_{ch} + R_D} \left( 1 - e^{- \frac{5R_{ch} + R_D}{L_1}(t - t_2)} \right) \]  
(14)

As coil 1 is still open circuit and coil 2 is connected to capacitor cell 3 the current level in coil 1 at the end of the magnetisation period \( I_{L1}(t_1) \) appears as the initial current level at the start of the demagnetisation period as shown in equation (14). In order to drive the identical peak current at the beginning of the demagnetisation period the magnitude of the inductor voltage across coil 2 must be higher than the inductor voltage across coil 1 at the end of the magnetisation period:

\[ |V_{L2}(t_2)| < |V_{L2}(t_3)| \]  
(15)

This is because the voltage across coil 2, \( v_{L2}(t) \), must be equal to the sum of the conduction voltages across the MOSFETs, the conduction voltage of the anti-parallel diode and the capacitor cell voltage, whereas in the magnetisation period the voltage across coil 1, \( v_{L1}(t) \), is the sum of the cell voltage minus all the conduction voltage drops.

A higher secondary voltage with equal currents results in the instantaneous power output being higher than the instantaneous power input during magnetisation. Therefore, to satisfy conservation of energy the demagnetisation conduction time must be shorter than the magnetisation conduction time: \( (t_3 - t_2) < (t_1 - t_0) \). The energy during the demagnetisation period must be equal to the energy during the magnetisation period thus:

\[ E = \int_{t_0}^{t_1} |v_{L1}(t)| i_{L1}(t) \, dt = \int_{t_2}^{t_3} |v_{L2}(t)| i_{L2}(t) \, dt \]  
(16)

Period 4 – t3 to t4 – Non-conduction period

When the MMF in the coil falls to zero there is no coil voltage and diode D2a stops any reverse conduction. Although the switches are all still on in the non-conduction period no current is flowing. All switches are turned off eventually in this period. Simulation and practical results show that a turn-off time of 500ns before the end of the time period T is sufficient.

III. CONVERTER CONTROL AND SIMULATION

The principal operations of the converter described above apply to energy transfers between any capacitors in an n-number connected capacitor bank. The multiplexer connects the required capacitors and the selector activates the correct coils depending on the coil current directions. The control states for the case C1 – C3 are shown in Table 1.

Table 2 illustrates the switching states employed by the controller for any given combination of source and sink cells. Column 1 lists all combinations of source and sink capacitors depending on the order in the capacitor stack (odd or even number). Column two shows the voltage polarity across coil 1 during the magnetisation \( t_0 \) to \( t_1 \) and demagnetisation period \( t_2 \) to \( t_3 \). Column three shows the appropriate switching states for the magnetisation period \( t_0 \) to \( t_1 \) and the demagnetisation period combined with the non-conduction period \( t_2 \) to \( t_4 \).

![Table 2](image)

Table 2 – General switching states for any combination of energy flow paths

For the purposes of proof of concept of the equalisation circuit a simulation model was developed in both SaberRD and PLECS. The capacitor cell model is based on the 2200F Li-Ion pouch cell prototypes with a datasheet nominal series resistance of around 1.5mΩ. Self-discharge effects are not considered. All internal resistance values have been taken from datasheets. The transformer was modelled using a pair of inductors coupled through a linear core (assuming no saturation) with an ideal coupling coefficient. The magnetisation period was fixed to half the switching time period; \( (t_0 - t_1) = \frac{1}{2f} \). Operating the converter with its maximum duty cycle of 50%.
The simulation parameters for the components are listed in Table 3.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET resistance</td>
<td>44mΩ</td>
</tr>
<tr>
<td>Selector diode resistance</td>
<td>1mΩ</td>
</tr>
<tr>
<td>Zener diode resistance</td>
<td>0.4mΩ</td>
</tr>
<tr>
<td>Converter switching frequency</td>
<td>4kHz</td>
</tr>
<tr>
<td>Primary and secondary winding inductances</td>
<td>6µH</td>
</tr>
<tr>
<td>Winding coupling coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Cell capacitance</td>
<td>2200F</td>
</tr>
<tr>
<td>Cell capacitor equivalent series resistance</td>
<td>1.5mΩ</td>
</tr>
<tr>
<td>Dead time period (t1 – t2)</td>
<td>500ns</td>
</tr>
<tr>
<td>Magnetisation period (t0 – t1)</td>
<td>125µs</td>
</tr>
<tr>
<td>Zener diode voltage</td>
<td>8.2V</td>
</tr>
</tbody>
</table>

The operation based on a circuit balancing 5 Li-Ion capacitors has been simulated. Figure 5 shows simulated waveforms for the converter operating at 4kHz with the primary winding inductance of L1=44µH. The voltage $v_{L1}(t)$ and $v_{L2}(t)$ are fully symmetrical as expected. During the magnetisation period both voltages drop over time. That is because the raising current $i_{L1}(t)$ produces an increasing voltage drop across the MOSFETs S1, S2, ST1a and the selector diode D1b. Likewise a voltage drop in the demagnetisation period is observed. The simulation in Fig. 5 shows further that the demagnetisation process is much shorter than the magnetisation process as explained earlier.

Figure 6 shows further that the demagnetisation process is much quicker than the charging process as explained earlier.

The simulation model was running over 20s comparing the rate of cell voltage change which is an important characteristic for active voltage balancing circuits. The change was measured for three inductance values: 6µH, 20µH and 44µH. Figure 6 shows the merging of the two capacitor voltages $V_{C1}$ and $V_{C3}$ over 20 seconds (switching begins at $t = 1s$ and ends at $t = 19.5s$) for $L=44\mu H$. The starting voltage for $V_{C1}$ is 3.7V and for $V_{C3}$ is 3.65V. The figure neglects the transient voltage drop across the internal resistance of the capacitor cells for clarity.

Figure 7 shows the cell voltages merging over the same time period with a 20µH primary winding and Figure 8 shows equalisation over the same period with a 6µH primary winding. Switching ceases at $t = 16.5s$ after the two voltages have merged.

Figures 6-8 show that discharging of the source cell C1 is quicker than charging of the sink cell C3. This is the effect that the magnetisation period takes longer than demagnetisation period. This is due to the losses in the converter whereby not all energy which is released from the
source cell is delivered to the sink cell and would be an effect of loss in all equalisation converters. Table 4 compares the rate of cell voltage change factor (RCVC) – which is a measure in the speed of equalising different cell voltages - and the maximum coil current (iL). RCVC is expressed as the change of the voltage difference prior and after equalisation over the equalisation time:

$$RCVC = \frac{\Delta V_{\text{before equalisation}} - \Delta V_{\text{after equalisation}}}{\text{equalisation time}}$$  \hspace{1cm} (17)

For example, from Figure 6:

$$\Delta V_{\text{before equalisation}} = V_{C1}(t = 1s) - V_{C3}(t = 1s) = 3.7V - 3.65V = 0.05V$$  \hspace{1cm} (18)

and

$$\Delta V_{\text{after equalisation}} = V_{C1}(t = 19.5s) - V_{C3}(t = 19.5s) = 3.682V - 3.659V = 0.023V$$  \hspace{1cm} (19)

The equalisation time is 19.5s - 1s = 18.5s, thus RCVC = 1.46mV/s.

Table 4 – Simulated equalisation rate for each winding inductance

<table>
<thead>
<tr>
<th>Inductance (µH)</th>
<th>RCVC (mV/s)</th>
<th>Maximum coil current iL(t = t1) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.2</td>
<td>22</td>
</tr>
<tr>
<td>20</td>
<td>2.3</td>
<td>14</td>
</tr>
<tr>
<td>44</td>
<td>1.5</td>
<td>8.5</td>
</tr>
</tbody>
</table>

IV. OPERATIONAL MEASUREMENTS

A prototype converter has been constructed and operated to demonstrate the principle of operation. A photograph of this prototype is shown in Figure 9.

![Figure 9 - Photograph of converter](image)

Figure 9 - Photograph of converter

For the purposes of technology demonstration a prototype has been constructed with a total of five cells (maximum stack voltage of 19V) but to the specification of a system containing 20 cells (a maximum 76V stack). This corresponds to a module specification for a commercial application.

For the converter the MOSFET switches IRF540N have been used for both the multiplexer switches and the selector switches. The IRF540N has high current capability (33A continuous) and low on state resistance (44mΩ). They are driven using HCPL-316 gate drive chips powered by 15V Traco Power TMR 3-2423 isolated DCDC converters. As is the case all previously presented equalisation schemes which have active switching components (with the exception of the one shown in Figure 1(a)) the switches in the proposed circuit ‘float’ relative to the stack ground since they are connected to different nodes along the cell stack. There is therefore a requirement in each of these circuits for gate drivers which have isolated supplies. Since this requirement is not singular to this circuit solution it does not represent an increased cost compared to existing circuits.

Various methods have been proposed in literature for multiplexing measurement of the cell voltage to the controller [25-27]. For simplicity in the case of the technology demonstrator described in this paper the differential voltage measurement of the cells is achieved using the AD629 high common mode rejection difference amplifier. The converter control is achieved using the Microchip 33FJ64GS610 dsPIC; a 16-bit 50MIPS architecture. This model processor has eight pairs of independent PWM channels which have individually addressable frequency, duty and phase values. The total of 12 required independent PWM channels required for the prototype leaves four spare channels. The control signals for all MOSFETs are created by using the master PWM counter. Figure 11 shows the schematic of the circuit.

For the purposes of analysis of the proposed equalisation scheme the operation of the hardware described above is identical to that of the simulated system described in section III whereby equalisation takes place between the first and third cells on the stack.

Figure 10 shows the measured voltage and current waveforms for the circuit in operation with a switching frequency of 4kHz and a winding inductance of 44µH.

![Figure 10 – Measured converter voltage and current waveforms, f = 4kHz, Lp = 44uH](image)
Comparing the results to the simulated results in section III shows that the peak current is lower than predicted in the simulations. The appearance of voltage oscillation ringing during the non-conduction period is another difference to the simulated data. The reduction in current is explained first. Figure 12 shows a magnified image of the waveforms during the magnetisation period. As shown in Figure 12, at a time just before the commutation point the instantaneous primary winding current is approximately 5.2A. The corresponding drop in voltage applied to the primary coil – which is a result of the conduction voltage drops of the MOSFET switches S1, S2, ST1a and the anti-parallel diode D1b as described in (3) – is approximately 2V. The series resistance of the conduction loop, excluding any resistance of the coil since the voltage is measured across it, can therefore be calculated using Ohm’s law as 380mΩ. This value is higher than the value of around 220mΩ which was calculated from the hardware datasheets of the MOSFET switches and the diode. The explanation for this increased series resistance lies in the added resistance of the protection circuit breakers (Figure 11) which, although essential for prototype commissioning and testing would not be present in a more developed version of the hardware.

The missing oscillation in the simulation can be explained because the simulated system employs an idealised transformer with no capacitance modelled. As an approximation, a small parallel capacitance added to each of the transformer windings may be used to model winding capacitance.

Figure 13 shows simulated results based on the additional resistance of the circuit breaker and adding parasitic capacitances of 20nF across the transformer. These waveforms match more closely the measured results.

Figure 11 - System level diagram of experimental apparatus

Figure 12 - Analysis of voltage drop during magnetisation. f = 4kHz, Lp = 44µH

Figure 13 - Adjusted simulation results for greater series resistance and added parasitic transformer winding capacitances
The equalisation converter has been operated with three values of inductance (6, 20 and 44\(\mu\)H) over 20s. Table 5 shows the rate of cell voltage change factor (RCVC) and the maximum peak current in coil 1.

Table 5 - Equalisation rate for each winding inductance

<table>
<thead>
<tr>
<th>Inductance ((\mu)H)</th>
<th>RCVC (mV/s)</th>
<th>Maximum coil current i(_L) (t = t1) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.1</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>1.4</td>
<td>8.4</td>
</tr>
<tr>
<td>44</td>
<td>1.1</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Figures 14-16 show the equalisation converter performance using 44, 20 and 6\(\mu\)H primary winding respectively. The equalisation performance shows that two cell voltages do indeed converge as predicted however, as would be expected from the increased resistance, more slowly.

![Figure 14 - Voltage equalisation over 20s. f = 4kHz, L1 = 44\(\mu\)H](image1)

![Figure 15 - Voltage equalisation over 20s. f = 4kHz, L1 = 20\(\mu\)H](image2)

Comparing all three figures it can be concluded that a lower coil inductance show better performance in terms of rate of cell voltage changes. Faster convergence will be achieved by eliminating the prototype circuit breakers and choosing MOSFETs and diodes with lower on-state resistances.

Figure 16 - Voltage equalisation over 20s. f = 4kHz, L1 = 6\(\mu\)H

Transformer-based active voltage balancing circuits have become an attractive solution for efficient voltage balancing for in series connected capacitance devices such as Li-Ion capacitors. However, multi-winding transformers are not feasible for a large number of in series connected capacitor cells. A new converter topology is presented that allows the use of a classical two windings transformer utilising a multiplexer and a selector circuit. This circuit can be applied to any number of capacitors in series.

The performance of the proposed circuit is analysed and has been explored through simulation. The proposed equalisation converter has been constructed and tested and shown to operate almost as expected. Some behaviour, such as the voltage ringing, has been attributed to parasitic effects of the prototype as constructed and further study may allow for the mitigation of these effects.

The proposed converter has a relatively good equalisation rate when operating in conjunction with the cells of the capacity used for this work. Equalisation rate is dependent on the losses in the equalisation circuit and the capacity of the cells in the stack. The equalisation of the presented converter could be improved when implementing switching devise with lower internal resistances.

VI. REFERENCES


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